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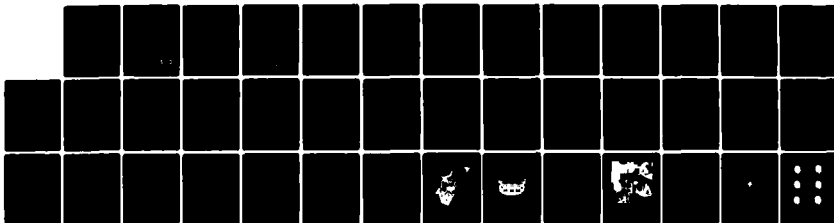
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SOLAR MAGNETIC FIELDS STUDY

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Final Report
1 May 1978 - 28 February 1983

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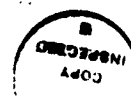
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SUMMARY

This report describes a series of observations of solar magnetic fields. These observations were made using narrow band filters and active seeing correction systems developed at the Lockheed Palo Alto Research Laboratories. New data has been obtained concerning the strength and size of solar magnetic field elements, and which sets an upper limit on the strength of the inner network fields. A number of new devices were first used for scientific observations under this contract. These included new tunable birefringent filters, an image motion compensation system, and most recently a 57-actuator seeing compensation system. The performance of these devices is described in detail in this report.

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INTRODUCTION

The principal purpose of this contract has been to use unique technology developed at Lockheed for the purpose of studying the dynamics of the solar atmosphere. In particular, new image stabilization methods have vastly improved the quality of scientific data obtained, and have also contributed to the ease of data reduction by eliminating the need for re-registration of images.

The chief thrust of the program during the last year has been the application of Lockheed active mirror technology to the problem of wavefront correction during solar observations. It is possible to envision two ways in which such an active mirror might improve the quality of ground based solar observations. The obvious benefit is the improvement of image resolution as obtained under less than ideal seeing conditions. Such an improvement would allow the study of the dynamics of solar fine structure by improving the probability that long sequences of high resolution images could be obtained and studied. The active mirror system also will permit the measurement of solar atmospheric properties which could not be reliably measured in the past. The mirror permits short sequences of observations to be made under conditions which effectively eliminate image changes resulting from seeing. Therefore, observations which require sequences of images to be made in different wavelengths and polarizations can now be performed with the assurance that seeing-induced variations between images will not cause errors when the images are combined to display the desired atmospheric parameter. A prime example of such a measurement is the determination of the solar vector magnetic field.

It should be emphasized that the improvement in the scientific content of observations made with the active mirror system is not merely in the ability to improve the spatial resolution of observations which are already being made at reduced resolution. Currently available information suggests that many important physical processes in the solar atmosphere occur only on a very small spatial scale, perhaps on the order of a tenth of an arcsecond. Magnetic field elements are known to be very small, and it is not an exaggeration to say that any phenomenon associated with them probably requires resolution of this order of magnitude in order to observe and understand the true

nature of the physical processes involved. It is reasonable to believe that the active mirror will be a necessary tool for the understanding of phenomena ranging from solar flares to the solar cycle itself.

The active mirror used in the contract was developed at Lockheed under company funding. The purpose of the contract was to make it possible to test the mirror at the Sacramento Peak vacuum tower telescope. Delays in the construction of the mirror postponed the test observations until January of 1983 when a two-week observing run was scheduled. During that run a series of storms allowed only one and one-half days of usable sunlight. Although no scientific observations were made, this observing run did serve to identify a number of technical problems with the mirror system as used at the vacuum tower. A second run was arranged, to be made for two days at any time in February that the sun was likely to be out. The run was made on the 21st and 22nd of February. Seeing conditions during the run were extremely bad, with uncompensated resolution averaging about 6 arcseconds. The mirror performed very well, however, and demonstrated a consistent improvement in the seeing to around 2 to 3 arcseconds. In seeing conditions as bad as those prevailing during the second run, it is not generally possible to reach the telescope diffraction limit with any type of atmospheric correction system, and most previous active mirrors are unable to even produce a visible improvement in the image. The Lockheed mirror, however, is designed in such a way that it will produce the best possible correction, even under the worst seeing conditions. It demonstrated this ability in February.

Further observations using the active mirror will be conducted in the spring or summer of 1983 at Sacramento Peak. These tests will be funded by Lockheed and will be designed to test the mirror's capability to achieve diffraction-limited telescope performance in more reasonable seeing conditions. At that time, the mirror will be operated in conjunction with one of Dr. Alan Title's tunable filters in a coordinated scientific observing program. This will serve to demonstrate the active mirror as a scientific tool.

The current state of the active mirror can be summarized as follows:

- 1) The mirror has demonstrated that it has the necessary performance to adequately correct the solar image at the vacuum telescope.
- 2) The mirror has demonstrated a dramatic improvement in image quality obtainable under bad seeing conditions.
- 3) The mirror is currently best described as an engineering feasibility model. It is not yet an easily usable tool for routine observations. This matter will be corrected in time for the observing run during the summer of 1983.
- 4) The scientific utility of the mirror system will be demonstrated in (we hope) dramatic fashion during the summer of 1983.

In addition to the demonstration of the active mirror system, this contract has been concerned with the investigation of parameters of the earth's atmosphere which are relevant to real-time seeing correction. The present active mirror configuration takes these measurements into consideration. The measurements made at Sacramento Peak have demonstrated that it is usually (maybe always) impossible to reach the diffraction limit of the vacuum telescope if the seeing is much worse than 2 to 3 arcseconds. This is a fundamental property of the atmosphere, and not a limitation of any particular active mirror system. It is, however, possible to achieve a substantial improvement in seeing if the mirror control algorithm is properly implemented. Seeing at the vacuum tower is generally limited to a bandpass below 100 Hz, and in 2 to 3 arcsecond seeing the isoplanatic patch (the area over which the image can be corrected) is about 3 to 12 arcseconds in diameter, with 6 arcseconds being a typical value. Under worse seeing conditions, the isoplanatic patch can be as small or smaller than the resolution limit of the telescope, making image correction to the diffraction limit impossible. The size of the required correction elements and therefore the number of such elements needed to cover a given size aperture varies with seeing. More elements are needed in bad seeing than in good. The 57 actuators used in the current mirror system should be adequate to produce a diffraction-limited image at the vacuum telescope in about 2 arcsecond or better seeing.

In addition to the work done recently with the 57-actuator seeing compensation system, Lockheed has been routinely using a piezoelectric tilt mirror image motion compensation system. This system has been in use for a number of years and is now an indispensable part of the Lockheed observing equipment. During the life of the contract, a number of scientific observing runs have been conducted at the vacuum telescope using the image motion compensation system. Several papers have resulted from these observations, and these are attached to this report as appendices. In general, it can be said that this work with image motion compensation has led to improvements in data quality which are outstanding in view of the extreme simplicity and low cost of the image motion compensation system. Every observatory should have several such systems.

The systems described in this report all depend on the use of silicon position sensors or quadrant detectors to track sunspots or pores in order to derive their correction signals. Although the image motion compensator has successfully tracked granule dark lanes in good seeing conditions, this cannot be considered a reliable mode of operation at the present time. There is a need for a wavefront sensor that can lock anywhere on the sun. Improved quadrant detectors have been developed at Lockheed which are capable of an order of magnitude greater sensitivity than those presently in use. These may serve to solve the problem. It may not be necessary to use more elaborate sensors such as correlation trackers. In fact, it may not even be very advantageous. The quadrant detector is capable of utilizing most of the information to be found within a typical isoplanatic patch. Although an array detector has higher resolution and therefore potentially can extract a greater amount of information from the image, it does so at a lower signal-to-noise ratio than that of a quadrant detector. A simple computation indicates that the information content of the two detector outputs is similar. Information derived from light coming from outside the isoplanatic patch is of no direct value in most situations, and so the wider area which can be covered by an array detector is of limited use.

To summarize, the technology of active seeing compensation is rapidly approaching the state where it can be considered a routine observing tool. It should be used routinely in that manner at Lockheed within the year. The observations carried out under this contract produced definite proof of the utility of such

systems in solar observations, if only under poor seeing conditions. The performance of the full 57-actuator mirror in good seeing was not evaluated, although this will be done soon under other funding. Significant scientific results have been obtained using the older image motion compensation system.

SCIENTIFIC RESULTS

This section of the report covers in detail the scientific results not covered in the papers in the appendix. In particular, the active mirror system is described in detail, and the results of the tests made under this contract are presented. The first part of this section deals with image compensation and active optical systems in general.

Seeing and Active Optical Systems

Active optical systems are not new as a concept. The basic idea is very simple. It involves sensing any departure of an optical system from its ideal configuration and then using one or more actuators to return it to the desired configuration. An active optical system can be as simple as the solar limb guiders in use at observatories everywhere, or as complex as a full wavefront correction system such as the one developed at Lockheed. The aberrations corrected need not result from atmospheric seeing. Systems with much slower response times than those needed for atmospheric seeing correction can correct primary mirror figure errors resulting from thermal or gravitational stress. Even systems designed to simply keep a system in focus or otherwise in alignment can be considered active optical systems. A prime example is an auto-focus slide projector.

The recent rapid development of active optics technology is the result of technological developments in image detector and information processing technology and to a lesser degree is a result of new actuator developments. New image array detectors allow image sensing with a degree of stability and accuracy which was impossible until very recently. The development of large-scale integrated circuits not only provided the detectors themselves, but also provided the means for rapid processing of their output. In some cases, the parallel development of high precision analog integrated circuits has been of equal or greater importance. This has been particularly true in the case of the Lockheed active mirror. The development of active optical systems is just another example of the information processing explosion of recent years.

Once an optical system has been analyzed and any departure from the desired configuration is detected, some sort of actuators must be used to bring it back into adjustment. For simple alignment systems, traditional servo motors or similar devices may be used. New electrodynamic actuators developed at Lockheed and elsewhere have provided significant gains in the performance of actuators for active optical systems. The new actuators are faster, smaller, and use less power than their predecessors. At present, however, piezoelectric actuators dominate the field of atmospheric image compensation. The speed, size, and efficiency of piezoelectrics is not likely to be challenged soon. Piezoelectric actuators have serious deficiencies in reliability, range of actuation, and open-loop performance, but they are adequate for the present job. New electrodynamic actuators are under development at Lockheed which should approach piezoelectric size, and which will have greater reliability, linearity, and actuation range. They should have adequate speed and efficiency for atmospheric compensation. They will be tested for this application when they are available.

An active mirror system to be used for the purpose of atmospheric seeing compensation consists of a wavefront sensor which determines the quality of the image falling on the telescope focal plane, a mirror with a sufficient number of actuators to remove whatever distortions the atmosphere may generate, and a control system which ties the two together. None of these three major components can be considered apart from the other two, and the entire system must operate in an environment which is determined by the seeing at the observing site. The Lockheed design was developed after approximately seven years of experience in the design and construction of active optical systems, and after two years of observations at Sacramento Peak specifically designed to determine the seeing characteristics there.

Equally important in the development of the active mirror was the several decades of experience in observational solar astronomy accumulated at Lockheed Solar Observatory. This experience was invaluable in providing the necessary background to determine what compromises could be made without limiting the usefulness of the mirror as a tool for observational astronomy.

Seeing characteristics can be quite different at different observing sites, not only in regard to the overall quality of the seeing experienced at that site,

but also in the characteristics of the wavefront distortions that produce the blurred and distorted images that are the end result of those distortions. It is not necessarily true that a good site for an image compensation system will have good uncompensated seeing, or that a site with good uncompensated seeing is necessarily a good site for a compensated imaging system. It is also true that seeing quality, whether compensated or not, is a function of telescope aperture. In the next few paragraphs, we will describe some of the factors that can affect seeing. We will then discuss the results of seeing tests carried out at Sacramento Peak under this contract and their implications for active mirror performance at the vacuum tower telescope.

Figure 1 shows the major sources of seeing at most locations. Although this model is rather oversimplified it serves to illustrate the basic principles which must be kept in mind when evaluating an observing site. Seeing generated by the atmosphere is the result of local index of refraction variations which result from local fluctuations in air density. These fluctuations occur on time scales varying from about .01 seconds to as much as a minute, and on spatial scales varying from less than a millimeter to many meters. They are the result of thermal and pressure variations arising from local atmospheric heating or from wind shear turbulence. Since air is a relatively poor conductor of heat, the atmosphere can be considered purely adiabatic on the time scales considered here. Thus, all such localized inhomogeneities can only dissipate through physical mixing of the atmosphere. This means that we can consider all seeing to be associated with turbulence.

The major sources of turbulence in the atmosphere are illustrated in the figure. The first, universally present, is near ground level. The sources are wind generated turbulence caused by wind flowing around obstacles on the ground and thermal convection caused by uneven solar heating of objects on the surface. The second is turbulence at any inversion layer which may be present. Inversion layers are generally associated with wind shear conditions, and some amount of turbulent mixing is generally also associated with the sharp thermal gradient across the inversion. The inversion layer in the Los Angeles basin, for example, generally occurs about 1000 meters above the surface and generates mild turbulence with relatively large characteristic spatial dimensions. The next layer of turbulence happens as a result of wind

flowing over irregular terrain such as mountain ranges, and occurs at roughly the altitude of the peaks. Although the effects of mountain lee waves can extend to extremely high altitudes, the flow is usually laminar at higher elevations. The last major source of turbulence is that associated with the tropopause, a universally present inversion layer at an altitude of about 10,000 meters. The degree of turbulence at the tropopause is vastly lessened if the jet stream is as far away as possible, a condition best found in the southern part of the United States.

A source of turbulence not shown in the figure which can be of extreme importance is thermal convection within the telescope tube. The vacuum tower, of course, was constructed expressly to eliminate this source of seeing. This problem is particularly severe with solar telescopes because of the high light intensities encountered in solar images.

The effects of the different sources of turbulence on seeing are also summarized in Figure 1. Ground level turbulence tends to be structured on a very small spatial scale and therefore to require a great many actuators to properly correct. For example, if the characteristic spatial scale of the turbulence is 5 millimeters, it would require approximately 30,000 actuators to properly correct the vacuum tower telescope aperture. This is presently impractical and will remain so for the foreseeable future. The same considerations apply to turbulence inside the telescope tube. The best way to fix this type of turbulence is to avoid it. Any site which has these sources of turbulence as the major contributors to seeing is a poor candidate for compensated imaging. Fortunately, the vacuum tower has been built expressly to eliminate these sources of seeing. (Ground level turbulence is the reason why it's a tower.)

Turbulence originating high in the atmosphere usually has a relatively large characteristic spatial dimension and therefore needs fewer actuators to correct. However, the farther away from the telescope the turbulence occurs, the smaller the angle subtended by a typical turbulence element, and therefore the smaller the isoplanatic patch. Accordingly, it is best to keep upper level turbulence as close to the telescope as possible. This can be achieved by choosing a southern latitude to keep away from the jet stream and by avoiding

mountains extending above the observing site. This is one case where a site which is bad for uncompensated seeing may be good for image compensation. Mountain top sites are noted for bad seeing generated by terrain-induced turbulence, but since this turbulence occurs close to the telescope, it should be easily corrected by a compensated imaging system provided that the turbulence is not generated so nearby that it has the small spatial scale characteristic of ground level turbulence.

All of the above factors suggest that the vacuum tower telescope at Sacramento Peak should be an ideal site for compensated imaging. Other sites which suggest themselves are Big Bear Observatory and anywhere in the Los Angeles basin. In Los Angeles, the sole source of turbulence in the summer is often the inversion layer at about 1,000 meters. Measurements made by Lockheed at the Rye Canyon facility in Saugus often showed isoplanatic patch sizes as large as 12 arcseconds.

The Lockheed Active Mirror

Lockheed Solar Observatory has developed a number of different high-performance, tunable birefringent filters over the past several years. One of the major motivations for the development of active mirror technology for solar observations was the need for more stable images which would allow the full power of these filters to be exploited. In particular, an image stabilization system was needed which would eliminate the need for reregistration of images when line scans and polarization pairs were to be analyzed. This need was first met with a simple image motion compensation system which was first used in conjunction with scientific observations made under this contract in the spring of 1980. That image motion compensation system proved to be an extremely valuable tool. It is now routinely used for observations. A similar system has been constructed at the National Council for Atmospheric Research after the Lockheed system was tested there. This image motion compensation system "agile mirror" is simple to operate and cheap to build. It uses a tracker capable of operating on sunspots or pores, and has tracked granulation dark lanes under ideal seeing conditions. It uses a Burleigh PZAT mirror and has a bandpass of about 2000 Hz.

The active mirror tested at the Sacramento Peak vacuum tower telescope in January and February of 1983 has 19 segments with 3 actuators per segment for a total of 57 actuators. Each segment is capable of independent motion in two axes of tilt and in piston. The segments are hexagonal in shape and are about 1.1 inches across the flats. Together they form a mirror about 5.5 inches in diameter, a good match for a 6-inch optical system. The actuators are piezo-electric stacks operating at a maximum voltage of 450 volts and with a maximum range of 9 micrometers. The mirror is normally operated with a type 1 servo with the unity gain crossover at about 1 kHz. This bandpass is more than adequate for atmospheric seeing compensation, since seeing has little effect at frequencies above 100 Hz. The mirror is capable of operating at a unity gain crossover as high as 4 kHz. The segments are of modular construction and are capable of being removed and replaced with a minimum of realignment problems. This is an important consideration for a prototype system, and also allows easy expansion to a larger number of segments. Figure 2 shows the basic construction of the active mirror, and figures 3 and 4 show photographs of a single segment and the complete mirror respectively.

A unique characteristic of the Lockheed active mirror design is the control system. A major problem of active mirror technology is that control systems tend to be complex and expensive. This complexity is primarily a result of the fact that a great deal of information must be processed. It can also be the result of a mismatch between the mirror itself and the wavefront sensor used with it. If, as is often the case, the mirror is piston actuated and the wavefront sensor measures local tilt in the wavefront, then the control circuitry must derive the mirror control signals by means of a complex control matrix. The Lockheed system sidesteps this problem by using a wavefront sensor that allows the mirror to operate as 38 independent closed-loop servos in the tilt mode only. Phase information is not calculated directly. Instead of closed-loop phase control, the mirror relies on simply matching the edges of each segment with its nearest neighbors to produce a smooth surface. This system has the advantage that the mirror operates in an optimal way, even in extremely bad seeing when phase information is not meaningful because of the extremely small size of the isoplanatic patch. Other advantages are the extremely stable and failure tolerant behavior of the servo system because of the lack of closed-loop interaction between mirror segments, and freedom from

false locks which can occur with most closed-loop matrix control systems. The major assumption upon which this control system rests is that the distorted wavefronts which the mirror will be asked to correct will contain no step discontinuities. This is a valid assumption for the atmosphere. One disadvantage of the present design is the need to depend on the open loop linearity of piezoelectric actuators. The piston signals necessary to properly drive each segment to the best edge matching position are calculated by a network of operational amplifiers. Since these signals cannot be applied closed loop, their accuracy is degraded by the hysteresis and creep normally associated with piezoelectric stacks, as well as any temperature changes which may have occurred since the system was calibrated. The temperature dependence in particular can be a major problem when the mirror is used in locations where uncontrolled temperatures can be expected. Tests on hysteresis and creep have shown that these will have no greater effect than 1/10 wave in the visible, provided that the voltage on all actuators is smoothly increased from zero to the nominal operating voltage of 220 volts at turn-on. This procedure places the actuator at a reproducible point on its hysteresis curve. Voltage excursions normally encountered in operation have negligible hysteresis. Nevertheless, the problems encountered with thermal stability during tests of the mirror under this contract have shown that either the temperature of the actuators must be controlled or that an independent edge matching sensor must be used, perhaps an eddy current sensor. In the near future, the thermal problem will be attacked by actively controlling the actuator temperatures. Since only coarse control (to an accuracy of about 5 degrees F) is required, this should provide an adequate solution to the problem. A block diagram of the active mirror control system is shown in figure 5.

The wavefront sensor used with the active mirror is an old design, using individual lenslets to generate separate images of the sun from each of the individual subapertures of the telescope represented by the active mirror segments. The mirror is designed to work on sunspots and pores. The sunspot position as seen by each lenslet is monitored by a United Detector Technology (UDT) x-y silicon position sensor. While these detectors are not quite as accurate as quadrant detectors, they have the advantage that their null position can be electronically adjusted over a wide range. This characteristic allows convenient final alignment of the system without need for precise

mechanical positioning of the 19 separate detectors, or of unnecessarily precise tolerances on lenslet centering and positioning.

A photograph of the complete active mirror system is shown in figure 6.

An optical system layout is shown in figure 7. It will be noticed that a white light Michaelson interferometer is included in the system for the purpose of determining if the individual segments are properly adjusted in piston. Tilt alignment is accomplished by placing a quadrant detector at the compensated image focal plane, then electronically adjusting the individual tilt loops to produce perfectly overlapping images from all subapertures as measured by the quad cell. The agile mirror compensates for overall image motion and thus reduces the necessary range of the active mirror elements themselves.

Tests at Sacramento Peak Observatory

In January and February of 1983 the active mirror was taken to the Sacramento Peak vacuum tower telescope and tested on the sun for the first time. The first run was two weeks in length and provided only one and a half days of usable sunlight. (One additional day of sun could not be used because of continual power outages.) An additional two days of observing were arranged in the event that the sun should happen to shine during February. It was during this two-day interval that the best data was obtained, although the limited sunshine available during the first two weeks provided invaluable experience with the operating characteristics of the system. Some modifications to the mirror were made between the January and February runs. These will be discussed below.

The two-week run in January, in addition to the frustrations caused by the lack of sun, had the usual problems encountered when bringing a new instrument into operational condition. Tests using laser and mercury arc sources showed problems with thermal stability in the system, both in the actuators themselves and in the optical bench used at the tower telescope. Also, problems with the tower heating system compounded the difficulties by allowing wide fluctuations of temperature during the course of a day. Finally, inadequate

vibration isolation made the use of the white light interferometer extremely difficult. Fortunately, we had lots of cloudy days to work on these problems, and by the end of the two weeks had evolved a basic alignment procedure that took about an hour from a cold start and about half that amount of time for a simple readjustment for thermal drift. The system stayed in usable alignment for two to three hours after alignment except on those days when the tower heating system didn't work at all. We were therefore confident that usable data could be gotten with the mirror if we could manage to find a solid hour of sunshine.

While at the peak, we modified the mounting scheme of the UDT position sensors to allow easier alignment and compiled a list of changes to the electronics to provide easier adjustment of the system. Although all of the controls and alignment procedures worked well when the system was locked on a test laser beam or on the mercury arc source, some of the controls proved too touchy for easy alignment when used with a sunspot target with its relatively low contrast. Several segments of the mirror had poor optical figures because of stresses induced by glue bonds and had to be reglued to their supporting mounts. Finally, several UDT sensors showed out-of-tolerance sensitivity variations and had to be replaced.

In January, we did manage to achieve several mirror locks on the sun, and to demonstrate the following facts:

1. The mirror was capable of tracking quite small sunspots with sufficient potential accuracy to permit diffraction-limited performance at the vacuum tower.
2. The edge matching network operated basically as it should. Unfortunately there was no opportunity to test the network under seeing conditions which it might be expected to improve. It was turned on under very bad seeing conditions and, as expected, didn't help much. Nevertheless, it did produce signals of the right direction and magnitude to properly match segment edges while locked on a sunspot. It was, however, impossible to observe the edge matching directly with the white light interferometer because of optical bench vibrations and because the interferometer fringes in the present optical configuration disturb the operation of the wave-

front sensor so that a reliable lock cannot be achieved with the interferometer in operation.

3. During our one full day of sunlight, a full lock was achieved on a small sunspot late in the afternoon. The image, while very stable, was of poor quality. The reason for the poor image was found the next morning to be an infrared filter inadvertently left in the camera neutral density filter pack. Unfortunately, this turned out to be our last chance at the sun in January. The poor quality of the image made it impossible to evaluate the effects of the active mirror on image sharpness. One effect noted at this time was that the image appeared to be stable over a much larger area than that achieved by a simple agile mirror in similar seeing conditions. The area stabilized appeared to be about 15 arc seconds in diameter. Exact measurements were impossible because of the badly blurred image.

On the weekend of Washington's birthday, another two days of observations were made. More efficient alignment procedures had been developed, the poor segments in the mirror had been replaced, the substandard position sensors had been replaced, and the infrared filter had been removed from the filter pack. Those two days provided a day and a half of sunshine. Seeing, however, was very bad. It averaged around 6 arc seconds during the run. An "artificial sunspot" was used for system alignment. This consisted of a small piece of black tape placed at the telescope prime image. The tape provided a stable source for use in alignment. At this stage, another problem was found with the vacuum tower horizontal optical bench. Any change in weight distribution on the bench, or even a change in a person's position on the observing table caused changes in optical alignment sufficient to degrade the image significantly. A better optical table is a necessity before diffraction-limited images can be obtained routinely at the vacuum tower, with or without active optics. For the present, the problem can be solved by allowing no unnecessary people on the table during alignment, and then making observations with the people who did the alignment still on the table in the same positions. If seeing is as bad as it was during our two days, these extreme precautions need not be taken. The effects were noticeable using the artificial sunspot and also using the white light interferometer. They affect the image at around the 1/2 arc second resolution level.

Figure 8 shows the result of locking the mirror on the artificial sunspot after a complete alignment. It gives an idea of the optical precision of the active mirror system. The cross hairs are wire with an equivalent width of about $3/4$ of an arc second. The mirror seems clearly to be capable of at least $1/4$ arc second resolution.

One of the problems in demonstrating the effects of the active mirror is that unlike a simple tilt mirror, it cannot just be turned off in order to see what the seeing would be like if the mirror had not been used. This is because when the mirror control loop is turned off, the segments assume a figure which may not be flat, and which therefore may give an exaggerated idea of how bad the seeing actually is. Therefore, in order to fairly evaluate the performance of the active mirror, an optical flat was placed in the collimated beam just ahead of the mirror in order to provide a comparison image. The system was carefully aligned to be sure that no focus variations existed. The focus, in fact, was originally set with the optical flat in place. The active mirror was then aligned to focus at the same place. Figure 9 shows the image from the optical flat on the left, and on the right the image with the active mirror locked. There was generally an improvement of about a factor of two in image resolution from about six arc seconds to about three. The impression of a wide area of image stability seen in the January results was also confirmed. The final result is that the active mirror works impressively well at turning very bad seeing into so-so seeing. The edge matching network was turned on without showing any improvement in the compensated image, and there is reason to believe that no improvement should be expected under such seeing conditions. There was not sufficient time to test the edge matching system properly in February, but this will be done under Lockheed funding at a later time this year.

The status of the active mirror system at the end of this test can be summed up as follows. The mirror has demonstrated that it can be of significant value in improving image quality under at least some seeing conditions. It has not been demonstrated that the mirror can reach the diffraction limit of the vacuum tower under better conditions, but it has been shown that it has the necessary optical and electrical precision to do so if the atmosphere will allow it. The system is still very much a prototype, and cannot be considered

ready for use as a routine observational tool. Any instrument that requires an hour of alignment for every two of operation needs some additional refinement. It is unfortunate that a narrowband filter was not available for use with the mirror during the February run. This situation will be remedied this summer, but at present the direct impact of the mirror on the quality of scientific data can only be inferred. At the very least, the larger area stabilized by the active mirror as compared to a single agile mirror should improve the probability that a significant event can be observed at high resolution. Also, the improvement in the seeing by a factor of two cannot be without value for synoptic observations at medium resolution.

Implications for Future Systems

The most interesting result of these first observations was the substantial improvement in image resolution achieved under what can only be described as atrocious seeing conditions. This was a completely unexpected result, at least by me, and has some definite implications regarding the characteristics of atmospheric distortion as it exists at Sacramento Peak.

To my knowledge, no mirror has ever been operated in the way this mirror was in an actual atmospheric seeing test. The unique factor in this case is the 19 independent tilt loops operating without any effective phase coherence, but still capable of maintaining a perfect overlap between the images from each subaperture. The compensated image was really just 19 superimposed images from 19 independent 7-inch telescopes. It appears that the seeing we were faced with in February consisted mostly of large seeing elements which caused substantial blurring in the full aperture image, but substantially less across the smaller subapertures represented by the mirror segments. So long as the amount of blurring is large compared to the diffraction limit of the subapertures, a simple geometric argument shows that an improvement in blur circle diameter should be seen which is inversely proportional to subaperture size. (That is, the smaller the subaperture, the smaller the blur circle.) This would be the case in the instance where there was absolutely no structure in the wavefront other than a gentle curvature on a scale equal to the full telescope aperture--a simple focus error. As higher order terms are added, a lesser amount of improvement would be achieved until terms with a spatial

scale comparable to subaperture dimensions are reached. These cannot be improved at all. In the case of real turbulence, the question is: What amount of turbulence can be attributed to elements of a given spatial scale? In this particular case, at least enough of the seeing must have come from large-scale structures to allow at least a factor of two improvement in the image resolution. The fact that the resolution limit of the subapertures alone was not consistently reached argues that even had the edge matching network been properly calibrated, no further image improvement could be expected since there was obviously a fair amount of blurring occurring on a scale less than the 7-inch diameter of the subapertures. Otherwise, a resolution of about 0.7 arc seconds would have been achieved. The basic problem here is that there were simply not enough segments to properly compensate a 35-inch telescope. The interesting result of these observations was that even with this inadequate number of actuators a substantial improvement was achieved over a surprisingly large area of the sun. We were surprised because our previous analysis had been solely concerned with those conditions which were necessary in order to reach the diffraction limit of the full aperture of the tower telescope. Our previous analysis showed that under poor seeing conditions, the area which could be corrected, even with an infinite number of actuators, would be too small to be of interest. While this may well be true, it seems that the concept of a single isoplanatic patch size is inadequate. If a lesser degree of image improvement than the full diffraction limit of the telescope is of interest, then the area which can be corrected can be much larger than the traditional isoplanatic patch. The particular design of this mirror, with its independent tilt control loops, allows this fact to be dramatically demonstrated. It also means that a very simple and cheap mirror is possible. It would consist basically of the present Lockheed mirror without the edge matching network. It remains to be seen what sort of improvement in image quality can be achieved on a routine basis, but up to $3/4$ of an arc second, this mirror will do as well as anything else with an equivalent number of actuators. Three-quarters arc second seeing is pretty rare anywhere.

OTHER SCIENTIFIC RESULTS

This program has been in continuous operation since May 1, 1978. During that time, a wide range of scientific observations have been carried out using state-of-the-art instrumentation developed at Lockheed for the purpose of studying the dynamics of the solar atmosphere. This work has been somewhat different from most of the work done at the tower telescope, since the telescope has been used primarily to feed Lockheed instrumentation installed on one of the horizontal optical benches. Little or no work has been done using the auxiliary instruments at the vacuum telescope for scientific observations, although they have been used occasionally for filter calibration and similar tasks. The program then has been simultaneously valuable in generating new scientific knowledge about the sun and in developing new instrumentation, much of which has applications other than solar observations. This contract has been invaluable in providing the support to test new instrumentation under actual observing conditions, and in proving the utility of that equipment by making significant contributions to the field of solar physics. Several papers have been published. A list of abstracts is given in Appendix A. A summary of the results is given in the following paragraphs.

Throughout the contract period, the major scientific interest has been high resolution studies of solar magnetic and velocity fields in the solar photosphere. In 1978 results were obtained showing that the inner network fields were probably less than 100 gauss in strength, since they could not be observed in very high resolution magnetograms made using Lockheed narrow-band filters. These results ruled out the possibility that the fields were actually quite strong but unresolved. Further analysis on this subject was done in 1979 along with work that indicated that some fields reported by observers using the Kitt Peak diode array magnetograph were actually the result of misregistered images obtained with the continuously moving entrance slit of that instrument. Methods of using birefringent filters for two-dimensional solar spectroscopy were developed in 1979, which suggested that high-quality line profiles could be reconstructed from birefringent filter data.

In addition to scientific and instrumental investigations carried out in 1978-79, work was also done on computerized post-processing of solar images to remove misregistration and improve magnetic and velocity field sensitivity in photographic magnetograms. All quantitative analysis of film data was done using the Lockheed scanning microdensitometer and computer image analysis. Although these techniques can be extremely powerful, they tend to be time consuming and to preclude the possibility of analyzing large amounts of data. Therefore, in April of 1980, a fast image motion compensation system was used at Sacramento Peak for the first time. It proved successful in eliminating most of the previously bothersome registration problems. Further analysis of 1979 results uncovered evidence of lower photosphere cooling in larger network flux tubes, a phenomenon which may lead to pore formation. Indirect observations were made of strong transverse fields associated with a low lying flux loop in a small bipolar region. Results of Harvey and Stenflo indicating that true magnetic field strengths in the bright network are an increasing function of element size were confirmed. An observing run in August of 1980 used the image motion compensation system to obtain lambda scans in Mg 5173 and 5250.

In 1981, analysis of 1980 data continued, with an emphasis on emerging flux loops. High resolution observations of magnetic fields and filigree appear to show that the magnetic structures are indeed larger than the associated filigree. On an observing run in October of 1981 a great deal of time was spent analyzing seeing parameters at the vacuum tower. Conclusions were that the size of the required active mirror segments (as projected onto the telescope aperture) varied from 10 cm in 1 to 2 arc second seeing to less than 5 cm in 5 to 10 arc second seeing. This is based on the desire to correct the image to the diffraction limit of the telescope. (If these figures are typical, the present active mirror would suffice to correct about a 20-inch aperture to the diffraction limit in good seeing.) Measurements were also made of the temporal power spectrum of seeing disturbances which demonstrated that no significant power exists above about 100 Hz, with a peak power at about 10 Hz. Typical peak-to-peak image motion for a 7-cm aperture in good seeing was about 3 arc seconds. A good part of this motion may come from tower guider errors or wind shake.

The period during 1982 was chiefly spent waiting for the Lockheed active mirror to be completed, a flurry of activity in late 1982 finished the interfacing arrangements to the tower telescope, and the contract finished with the January and February 1983 observing runs described in detail above. The material summarized in this section is well documented in the various papers and presentations, abstracts of which are given in Appendix A.

OTHER CONTRACT RELATED MATTERS

The major anomaly in the otherwise more or less routine progress of this contract was a no-cost extension running from the original expiration date of September 30, 1982 to February 28, 1983. This extension was originally requested because it appeared that the birefringent filter planned to be used with the active mirror would not be ready on time. This proved to be true, but the real delay turned out to be completion of the active mirror itself which ran into unanticipated schedule difficulties, particularly in obtaining circuit card and in machine work needed for the mirror mechanical parts. In the end the mirror was not ready until after Christmas, and by that time the birefringent filter was no longer available, being needed for NASA contract work.

Additional observations with this equipment will be carried out with Lockheed support. The scientific investigations are continuing under a similar AFGL contract with Dr. T. D. Tarbell as principal investigator.

LIST OF CONTRIBUTORS

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R. C. Smithson
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A. M. Title

PREVIOUS AND RELATED CONTRACTS

Previous Contract:

Research on the Dynamics of the Solar Atmosphere, AFGL F19628-76-C-0044

Related Contract:

Spectral Imaging with a CID Camera, AFGL F19628-82-C-0030

APPENDIX A

ABSTRACTS OF PAPERS AND OTHER PUBLICATIONS

Ap. J., vol. 229, p. 387 (1979). Weak and Strong Magnetic Fields in the Solar Photosphere, Theodore D. Tarbell, Alan M. Title, and Stephen A. Schoolman
Lockheed Palo Alto Research Laboratory

We discussed very high-resolution ($1/2''$) magnetograms of quiet Sun and plage, which were obtained by using a tunable birefringent filter in Fe I 6302. A search for a turbulent bipolar field, using co-added and spatially filtered frames, is unsuccessful. Statistical analysis sets an upper limit of 50 gauss on the rms vertical component of such a field and probably rules out the possibility of field strengths exceeding 100 gauss in the inner network field observed at Kitt Peak. The area, total flux, and energy content of the strong (kilogauss) network fields are measured and compared with the upper limits for these properties of a hypothetical, widespread weak field. In quiet photosphere, a weak background field may contain interesting amounts of flux and energy, but the strong fields are dominant at higher levels and in plage. The total magnetic energy in quiet photosphere is roughly equal to the kinetic energy of granular and oscillatory velocities at the same level. By flux conservation, field strengths in the transition region are greater than 25 gauss in quiet network and 100 gauss in plage.

Bull. Amer. Astron. Soc., vol. 11, p. 631 (1979). Problems in the Detection of Weak Magnetic Fields on the Sun, T. D. Tarbell, Lockheed Solar Observatory.

A widespread, weak magnetic field in the solar photosphere could contain magnetic flux and energy in amounts comparable to those of the strong network fields. If the weak field is bipolar on a small enough spatial scale, it could have escaped detection because of seeing or aperture averaging in magnetographs. The inner network fields, seen at KPNO and Lockheed only when the highest possible sensitivity is employed, may be this turbulent background field. In this exhibit, I show examples of several effects which cause spurious bipolar magnetogram signals similar, but not identical in appearance, to

the inner network fields. A filter magnetogram is made by subtracting circularly polarized images in one or both wings of a Zeeman-sensitive line. When one wing (two images) is used, spatial misregistration causes intensity gradients to appear in the subtraction. An offset of 0.01 arcsec causes a spurious signal of 3-5 gauss rms, which is bipolar on a scale of 1-2 arcsec, for the line Fe I 6302. If the images are not simultaneous, seeing causes "rubber sheet" distortions of 0.1 arcsec or more. The background noise can be reduced by image processing to remove the random distortion and by averaging many pairs of frames. Temporal intensity changes also appear when non-simultaneous frames are used, at the level of a few gauss per second of time between frames. These can be reduced by using 4 frames with polarizations ordered as (RCP, LCP, LCP, RCP). When measurements are made in both wings, as in the KPNO magnetograph, analogous effects occur with Doppler gradients appearing instead of intensity gradients. J. Harvey of KPNO has provided convincing evidence that dv/dx leaks into the magnetogram, where x is the scan direction, because the moving entrance slit causes spatial misregistration between the measurements in orthogonal polarizations. In principal, this spurious signal can be detected and subtracted in real-time

Bull. Amer. Astron. Soc., vol. 11, p. 640 (1979). Using Tunable Filters for Two-Dimensional Solar Spectroscopy. H. E. Ramsey, S. A. Schoolman, R. C. Smithson, T. D. Tarbell, and A. M. Title, Lockheed Solar Observatory. Although tunable birefringent filters have been used to take filtergrams at different locations within line profiles (-scans) for many years, the wavelength difference between successive filtergrams has typically been comparable to the half width of the filter. We have demonstrated that, by changing the wavelength by an amount which is small compared to the filter half width, we can still see significant changes in the structure and brightness distribution of the solar atmosphere. This technique offers the possibility of reconstructing detailed line profiles arising from a two-dimensional area on the sun. Examples will be shown in which a Lockheed universal filter, with a bandpass of 140 m at 6300 , is stepped 20 m between filtergrams.

Bull. Amer. Astron. Soc., vol. 12, p. 915 (1980). A Simple Image Motion Compensation System for Solar Observations. R. C. Smithson, T. D. Tarbell, and A. M. Title, Lockheed Palo Alto Research Laboratory. We have built an

image motion compensation system to remove seeing jitter and telescope shake. A videotape movie of sunspot and pore observations shows its successful operation at the Sacramento Peak tower. Within roughly one arcminute of the target spot, the image is stabilized to a small fraction of the seeing disk regardless of the seeing quality. Measurements of the power spectrum of image motion and its effect on image sharpness are also shown. Image motion is detected by a quad photocell centroiding a sunspot or pore and is removed by a piezoelectrically driven tilt mirror controlled in a closed-loop servo of 500 Hz bandwidth. The system is simple to build and operate and has been used on several observing runs to improve the resolution of our filtergrams.

Paper submitted to SPIE Conference on Imaging Spectroscopy, 9-13 February,

1981: Imaging Solar Spectroscopy with a Tunable Birefringent Filter;

H. E. Ramsey, S. A. Schoolman, R. C. Smithson, T. D. Tarbell, A. M. Title, Lockheed Palo Alto Research Laboratory. In the past, solar physicists have routinely used narrowband and/or tunable filters to photograph the solar surface at wavelengths within a variety of spectral absorption lines. Some crude height resolution has been achieved in morphological studies by comparing images at different wavelength separations from the core of a strong line. Also, semi-quantitative measurements of Doppler shifts and magnetic fields (i.e., Zeeman splitting) have been inferred from intensity differences between frames at different wavelengths and/or polarizations within appropriate lines. Most work has been done with filters whose spectral bandpasses were comparable to or broader than the absorption lines of interest. In this paper, we describe extensive photographic observations with a very narrow filter (FWHM = 0.07 \AA at 5200 \AA), which can be tuned accurately through an absorption line in 0.01 \AA steps. We present "lambda scans" (sets of images at different wavelengths spaced throughout the line profile) for several lines formed at different heights in the atmosphere. The spectral line profile at any spatial point in the field of view can be constructed from a lambda scan. Study of these images has revealed several subtle shape effects in the line profiles of different solar structures. These include very narrow line cores of both emissions and absorption, asymmetries caused by velocity and magnetic gradients, and the divergence with height of magnetic field lines inferred from line core emission. A new filter system, with a 50% narrow

bandpass and a photoelectric array detector, is being built for both ground- and shuttle-based solar observing.

Bull. Amer. Astron. Soc., vol. 14, p. 924 (1982). Fine Structure in the Solar Magnetic Field, T. D. Tarbell, A. M. Title, Lockheed. We present observations made with the Spacelab 2 engineering model tunable filter at the Sacramento Peak tower telescope. The filter bandwidth is 75 mÅ at Fe I 5250, narrow enough to provide some line profile information. Images are recorded on film and analyzed digitally to make longitudinal magnetograms, Dopplergrams and photometrically-corrected filtergrams. The best frames have resolution better than 0.5 arcseconds. Results for several active regions are presented, illustrating the following: offsets between intensity and magnetic maps of faculae, predicted by magnetostatic flux tube models; variability in the relation between downdraft speed and magnetic flux; the spatial relationship between granulation and flux tubes of different sizes; greater inclination of field lines in dark penumbral filaments than in bright ones; extension of the penumbral fields far beyond the visible penumbral edge; a possible change in the magnetic fine structure of a complex active region during a flare. This work is supported by Lockheed IR funds and AFGL contracts.

ADDITIONAL TALKS AND PUBLICATIONS

- T. D. Tarbell and A. M. Title, "Zeeman Profiles and Magnetic Fields in a Simple Round Sunspot," Sunspot Conference, Sacramento Peak Observatory, 1981.
- T. D. Tarbell, "Small-Scale Solar Magnetic Fields," Colloquium on Solar and Stellar Rotation and Magnetic Fields, University College London, 1981.
- T. D. Tarbell, "Observations of Solar Magnetic Fields," IAU Symposium #102, "Solar and Stellar Magnetic Fields," Zurich, 1982.
- A. M. Title, "Filter Observations of Solar Magnetic Fine Structure," *ibid.*

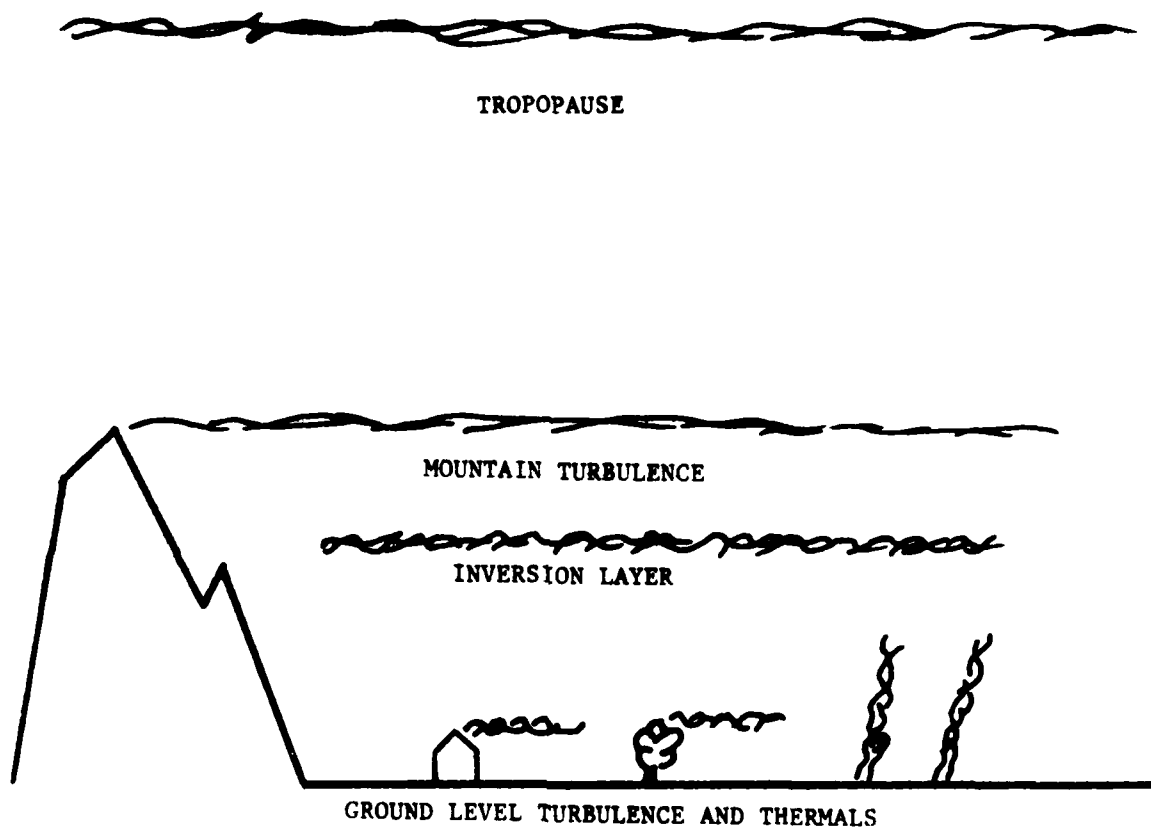


Figure 1. Major sources of seeing

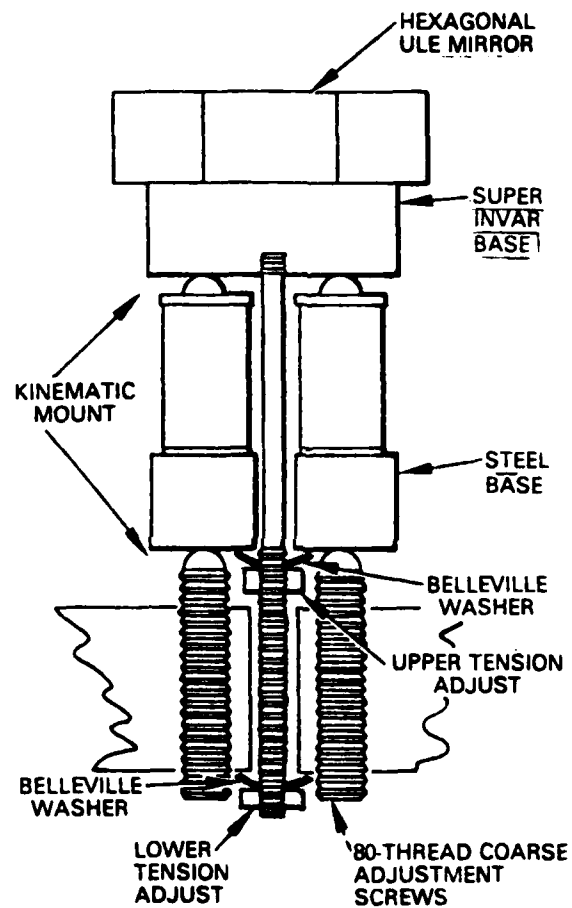


Figure 2. A diagram of the active mirror construction

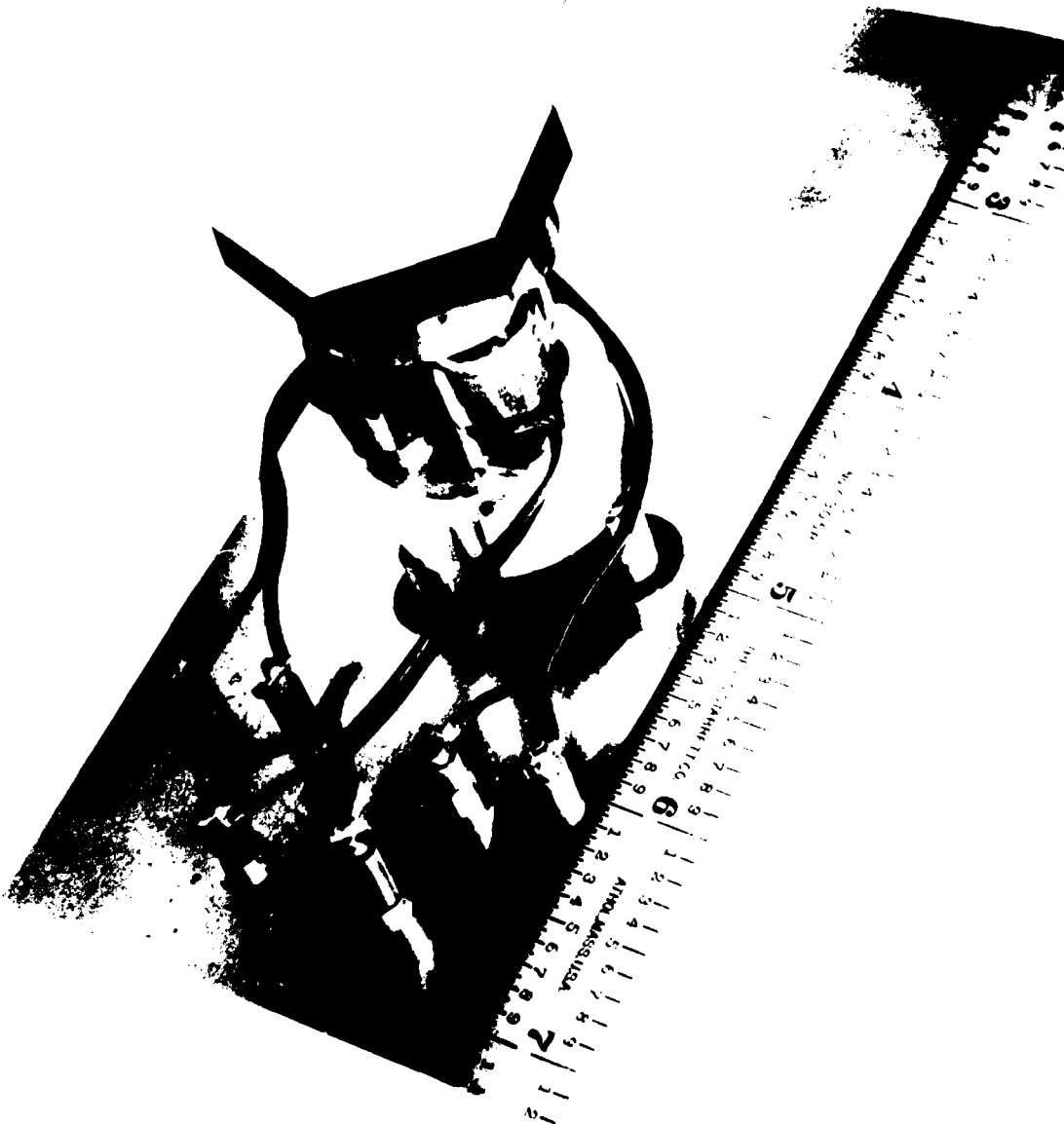


Figure 3. A photograph of a single segment of the active mirror

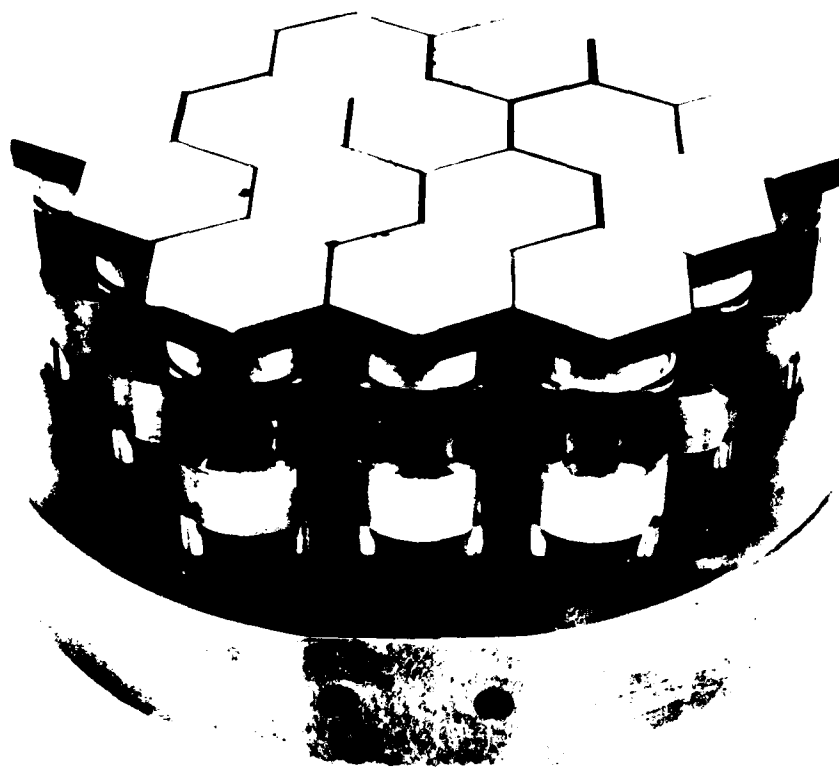


Figure 4. The completely assembled active mirror

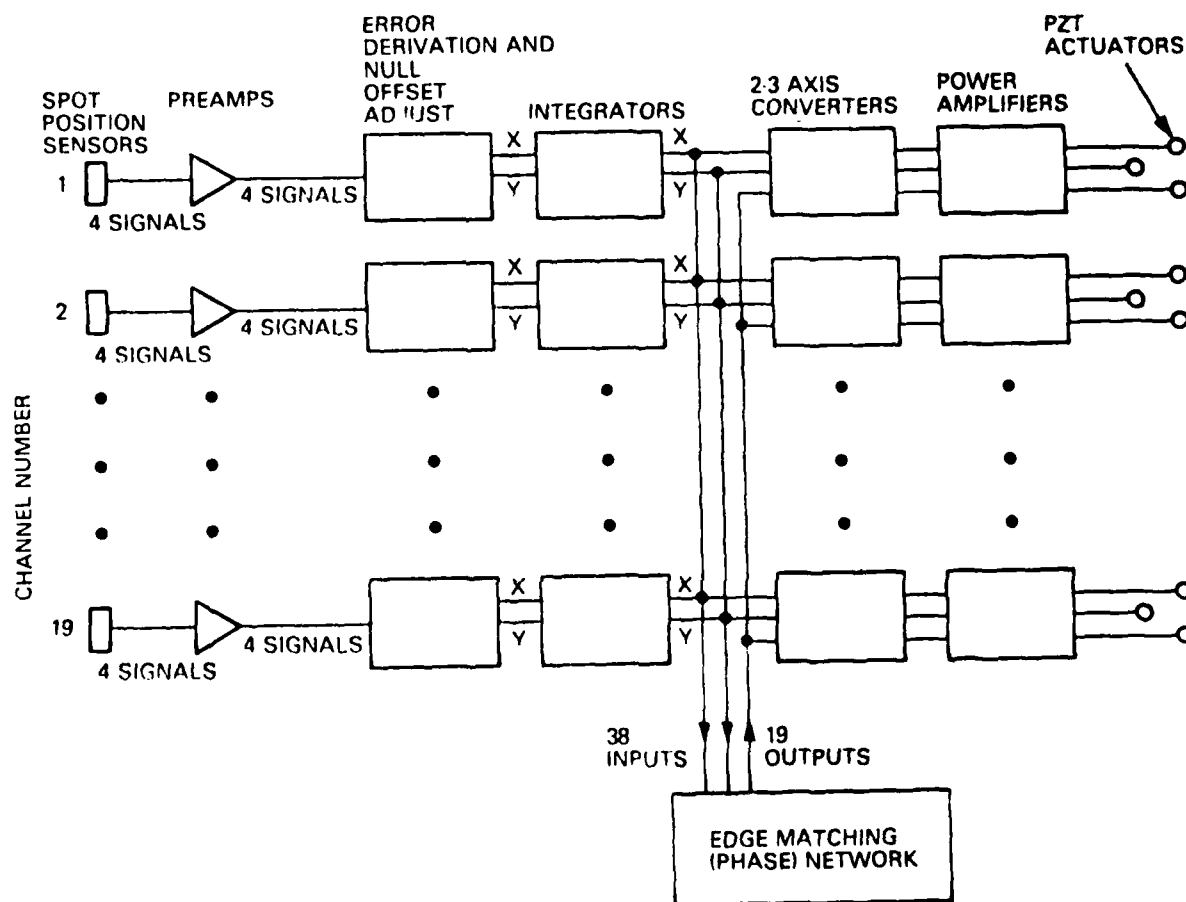


Figure 5. Block diagram of the active mirror control system



Figure 1. The complete setup.

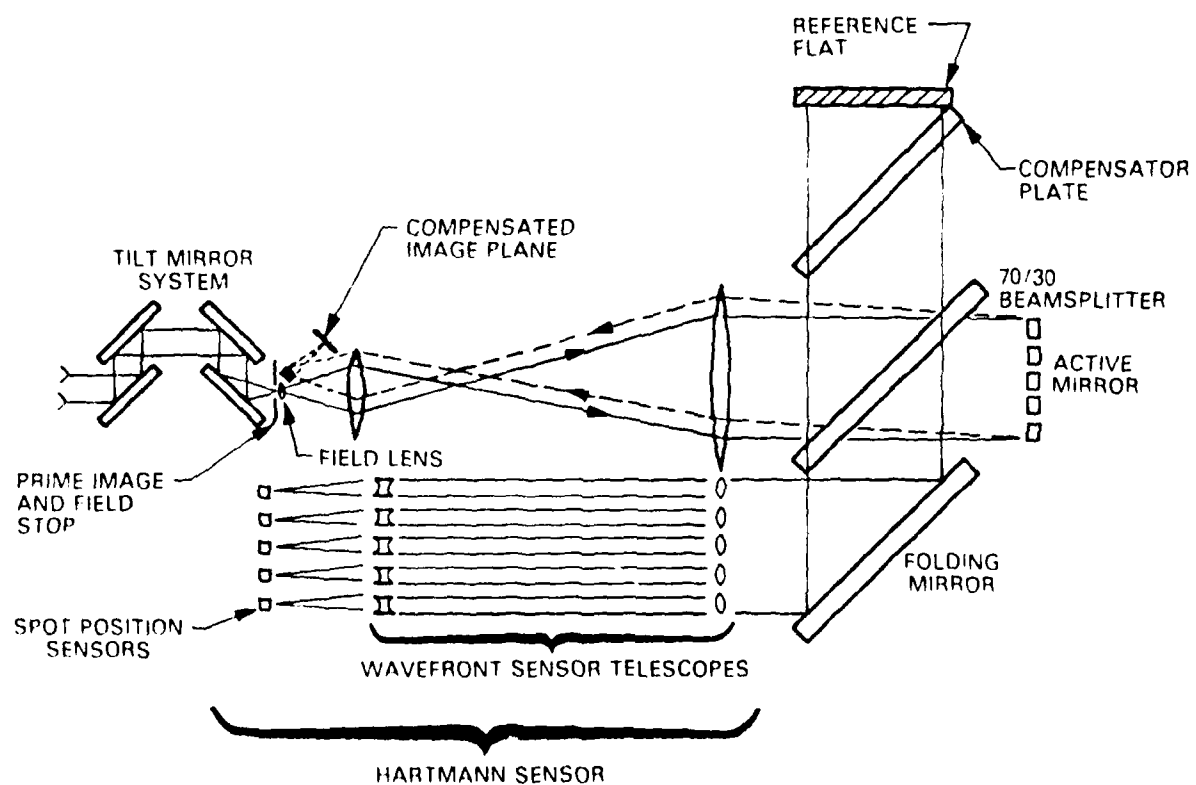


Figure 7. Optical diagram of the active mirror system

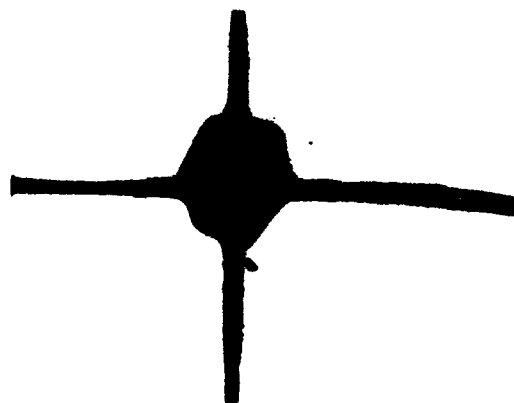


Figure 8. This image shows an "artificial sunspot." It serves to illustrate the limiting resolution of the active mirror system under ideal seeing conditions. The cross hairs are 0.75 arc seconds in width.

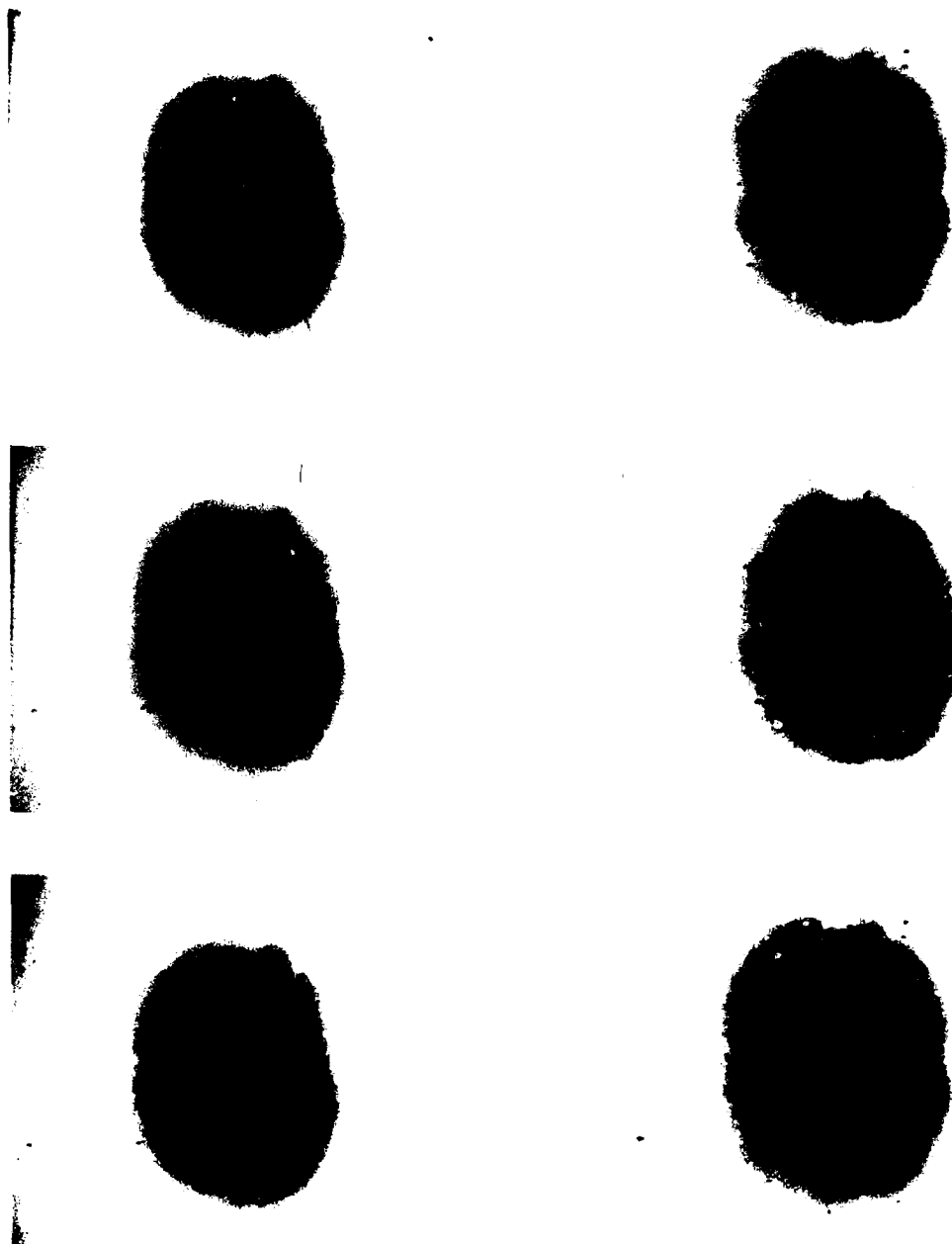


Figure 9. The three photographs on the left show typical images taken without the active mirror a few seconds after unlocking the active control loop. The three on the right are typical images made with the active mirror in operation.

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